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Kinetic Inductance Detectors Based Receiver Array Architectures for Imaging at THz Frequency

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***Abstract*— A novel strategy for broad band focal plane array design, resulting from the two years long cooperation between TNO and SRON (Space Research Organization Netherlands), is proposed. Its purpose is to couple the radiation from a Large F/D reflector system to an array of Kinetic Inductance detectors that are being investigated at SRON to be used in Space science missions such as SPICA.**

I. Introduction

This contribution will report on the status of the cooperation between TNO and SRON toward the development of high sensitivity, large bandwidth imaging arrays. The cooperation started almost two year ago [1] and its aim is to anticipate the needs of a future THz instrument that would constitute part of the payload of a scientific satellite for future deep space investigation in the Japanese mission SPICA (2017) [2].

Three challenging requirements would characterize such instrument: an extreme sensitivity (noise equivalent power NEP<10^{-19}), a large number of pixels and the decade BW.

The Kinetic Inductance detectors, KIDS [3], proposed by SRON, should help to satisfy the sensitivity requested for the actual receiver. Meanwhile the enhancement of the throughput which is necessary to fulfil the BW and pixel requirements is being addressed by TNO by proposing an integrated focal plane array loaded by dielectric lenses. It is essential for the feed arrangement to be designed in conjunction with the KID type receivers. This limits the designs options: in practice the same CPW structure hosts the low frequency resonator (GHz) read out signal and the slot antennas that absorb the high frequency (THz) incoming radiation.

The first phase of the work was aimed at the demonstration of the potentials of the KIDS to provide the required sensitivity. To this end a first 670 GHz, narrow band, single pixel design has been developed, manufactured and then tested at SRON.

In this phase a problem was encountered that is intrinsically associated to the use of the fully planar technology. The KIDS resonators are realized in Coplanar Waveguides (CPW). As anticipated slot antennas were chosen as most suited to couple THz radiation into the CPW lines. Unfortunately CPW lines support both even and odd electric field propagation. While the even mode is the desired propagating mode, the odd mode is associated to radiation and thus can seriously degrade the overall performances of the receiver. To overcome this problem in the previous phases of this work it was decided to resort to the development and application of air bridges whose main scope would be to short-circuit the odd mode. This has been successfully demonstrated in the first phase of the work. The team is presently dealing with the study of a way to suppress radiation from the odd mode that does not involve the use of a large number of air-bridges.

II. Report on the FIRST PHASE Results

A. Requirements from the SPICA mission

Three main requirements have been proposed by the scientists for the SPICA mission instruments that, when realized, would constitute major breakthrough with respect to the already advanced state of the art of sub-mm wave frontends. While the main *sensitivity* requirement (noise equivalent power NEP<10^{-19}) is essentially associated to the receiver technology, the other two major requirements are the *number of pixels* (in the order of the thousands) and the *BW*. Overall a decade BW is considered interesting for SPICA which at the present time is supposed to be divided in three separate bands and consequently investigated by three separate instruments. Given this scenario it is legitimate to imagine that if such targets will have to be achieved something new should arise. While SRON proposes KIDS for the sensitivity issue, TNO proposes Dielectric lenses for the BW Kilo-elements focal plane array. In the rest of this paper we will imagine a focal characterized by F/D in order of 10, and accordingly d approximately $10\ \lambda_0$ with reference to Fig.1, even if $F=2*D$ would probably suffice for a thousand element array. A BW of operation in the order of 15% is considered by the first prototypes. Novel designs which aim at 1:2 BW are being delivered to SRON as the paper is being written.

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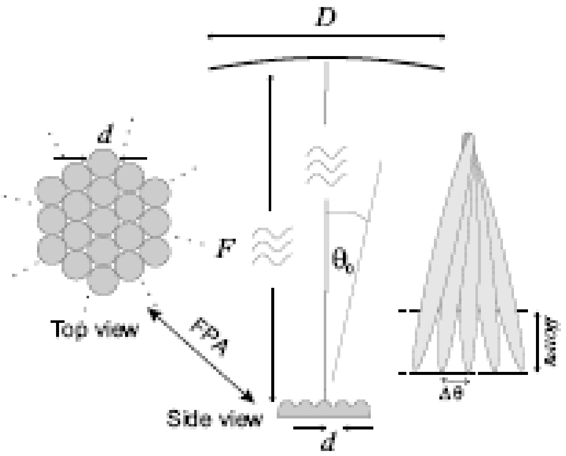

Fig. 1 Schematic view of a reflector system and focal plane suited to host feeds for multiple beam imaging.

B. Kinetic Inductance Detectors

Kinetic Inductance Detectors were originally proposed at Caltech by the Group of Jonas Zmuidzinas [4]. A proper discussion is outside the scope of this paper. However their basic working is relatively simple. A thorough line is realized in CPW technology an connected to an input (1) and output (2) of which it must possible to measure the S12 parameters in a band of a few GHz centered at frequency lower than 10 GHz. If the line is parasitically coupled to a resonant circuit, the S12 will be significantly lower at the resonant frequency, with the stop frequency band depending on the propagation properties of the transmission line that realizes the resonance. The concept is that if the line is realized in superconductive material kept at appropriate temperatures the properties of the line can be altered by an incoming EM signal which is coupled to the resonating line. In practice this signal could be at any frequency.

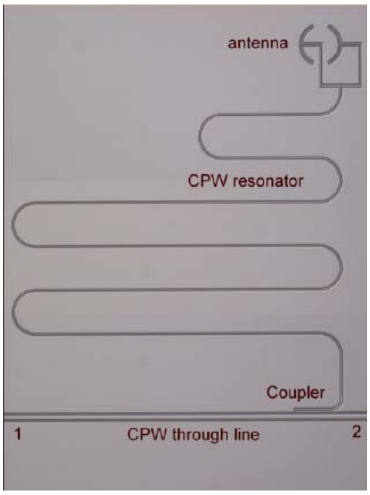

Fig. 2 The through line in the bottom of the picture, the resonating quarter wavelength (at GHz frequencies) line realized in Coplanar waveguide, and the twin arc slot antenna

C. Sub-mm wave First Implementation

After the preliminary scaled design of the antenna which we reported in [1], it was decided to manufacture a high frequency prototype of at 670 GHz to demonstrate the effectiveness of the novel type of KIDS that are developed at SRON. For the purposes of SPICA it is chosen that the frequency be high enough to demonstrate feasibility in the THz regime but low enough for the entire manufacturing to be done with optical lithography. The coupling from the sub-mm wave generator and the resonator line happens via the antenna whose demonstration is one of the purposes of this work. See Fig. 2 which shows the through line in the bottom of the picture, the resonating quarter wavelength (at GHz frequencies) line realized in Coplanar waveguide, and the twin arc slot antenna that couples the CPW to the THz radiation.

A two slot structure each of them excited with a CPW line is used. The two lines are then connected in parallel to achieve a unique feed. Note that the common feeding line, or filter, has been chosen to present characteristic impedance equal to 50 Ohm. Each of the two slots will present a real part of the impedance which is roughly 100 Ohm. Accordingly each of the lines connecting the two slots to the common feeding line will present approximately 100 Ohms too. The impedance bandwidth is in the order of 15%.

D. Measurement Set Up

Most of the work in the year went into the preparation of the measurement set up. The details are completely skipped in this communications as they will be the object of a dedicated contribution. It is however worth to highlight that once the printed circuit board with the Cristal with CPW circuitry was manufactured a dielectric lens antenna was glued to it, and the entire structure was blocked in a sample holder, see Fig.3. The sample holder was then installed in the cryogenic cooler that was kept at 300 mK in order to support the behaving as superconductor of the 150 nm Ta KIDS on Si.

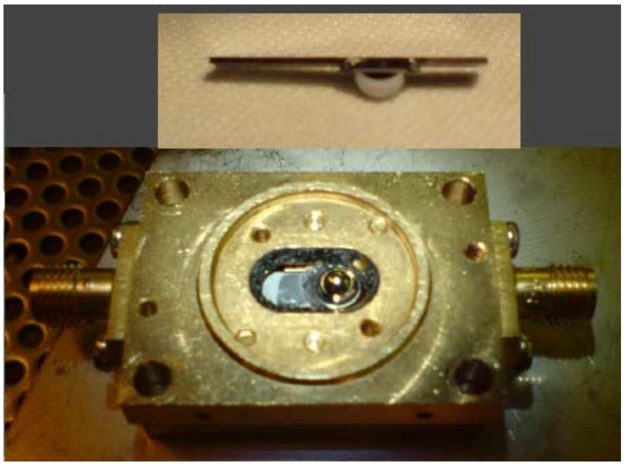

Fig. 3 The sample holder and a side view showing the synthesized elliptical lens antenna glued to the sample.

The sample holder was kept with dielectric lens pointing toward a coupling window which is cut in the side wall of the cooler so that power from a black body radiator, acting as known sub-mm wave power source could coupled into the lens. The incoming radiation source was then scanned around the window so that over time the field sensed at subsequent positions could be recorded by storing the phase variations of the S12 response in the GHz range.

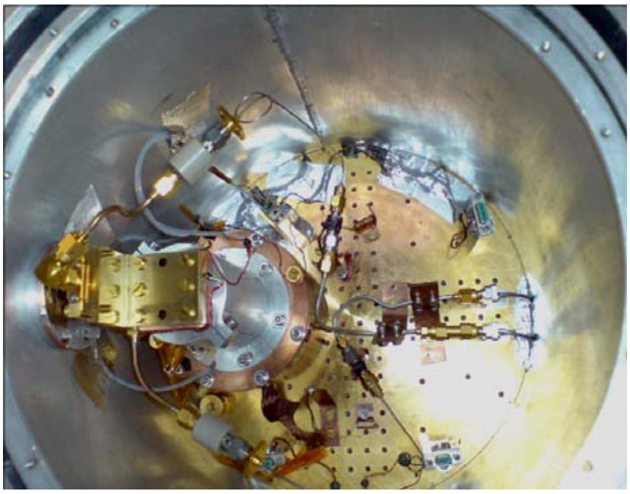

Fig. 4 The sample holder and a side view showing the synthesized elliptical lens antenna glued to the sample.

E. Air bridges

The first radiation patterns detected by the KIDs were very disappointing due to the importance of spurious radiation arising mostly from the parasitic radiation occurring from the feeding lines. In order to improve the quality of the patterns air-bridges were implemented, with details shown in Fig.5. Eventually the introduction of the air bridges led to good radiation patterns at 670 GHz. These patterns are shown in Fig.6 where they are also compared with the simulated patterns.

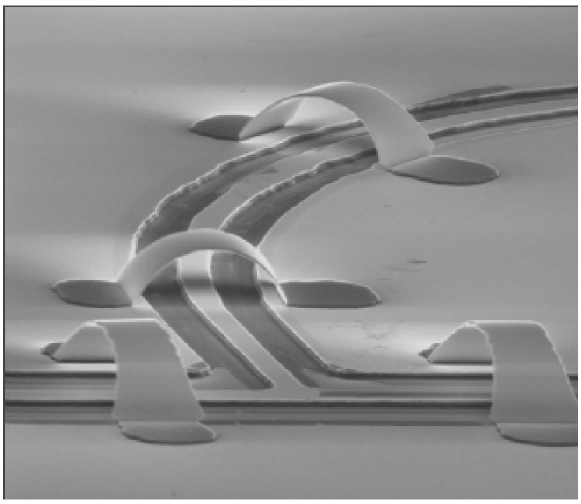

Fig. 5 Details of the air bridges realized in order to suppress the even electric field mode in the CPW lines.

Cross polarized levels are in the order of -10 dB with respect to polarized signal. At the present time it is thought that this might be due to the fact that the summation of the two signals arising from the two slots is only partially coherent due to the fact that significant losses occur in the two different CPW connecting to each slot before the in phase summing point is reached. These losses are actually associated to the actual excitation of the cooper pairs which is the cause of the alteration of the filter impedance and equivalent electric length.

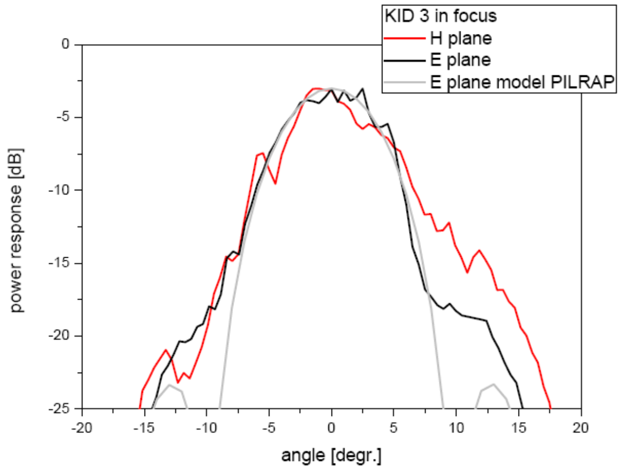

Fig. 6 E and H plane radiation patterns and comparison with expected results.

The co-polarized and cross polarized fields are shown in the contour plots in Fig.7 and 8 respectively.

F. Sensitivity

The measured optical responsivity was in the order of 30%.

- Given that the Kid was realized on Tantalum which is associated to low Q KID filters but is good for the for 300 mK setup
- Given that the measured dark NEP ~ $2.5 \cdot 10^{-16}$ W/√ Hz
- Given that the measured optical NEP ~ $8 \cdot 10^{-16}$ W/√ Hz
- Given that best Dark NEP is $6 \cdot 10^{-19}$ W/√Hz using device measured τ (half life time of cooper pairs with stray light and out diffusion).

The Inferred best Optical NEP is ~ $2 \cdot 10^{-18}$ W/√Hz .
This is a very good result placing this as one of the most sensitive receivers in its category.

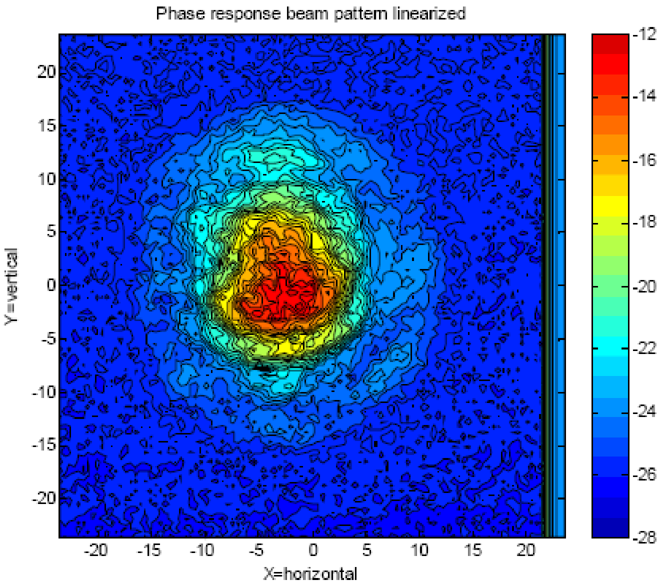

Fig. 7 Co-polar planar measured distribution

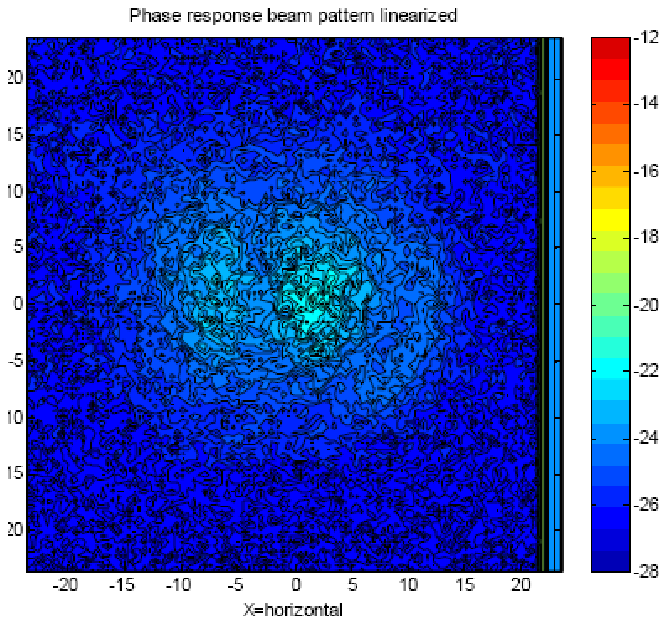

Fig. 8 Cross polar planar measured distribution.

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